

Supersymmetry as a physics beyond the standard model ^{*}

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Abstract

Here I briefly discuss why supersymmetry is considered a leading candidate of physics beyond the standard model. I also highlight the salient features of different supersymmetry breaking models. A few other symmetries, broken or intact, associated with any realistic supersymmetric model are also identified. This write-up is too simple-minded for an expert on supersymmetry. It is basically intended for those who are busy in other areas of high energy physics.

1 Introduction

Several experiments in the last few years have tested the standard model (SM) of particle physics [1] to an unprecedented accuracy. After the direct observations of the top quark and the tau-neutrino, only the Higgs boson remains to be seen to bring the search for SM particles to an end. Even though a 2.9σ signal of a neutral Higgs boson weighing ~ 115 GeV has of late been announced by the LEP Collaborations at CERN [2], the statistical significance nevertheless is too weak for the community to accept it as a discovery of the Higgs. As regards the parameters of the SM, the total and partial widths of the Z boson have been measured at LEP to a *per mille* accuracy [3], and the agreement with their SM predictions is unquestionable! Although a few discrepancies like the ' R_b - R_c crisis' and the 'ALEPH four-jet events' at LEP and the 'high Q^2 anomaly' at the electron proton collider HERA at DESY surfaced in the last few years, they all disappeared with further accumulation of statistics and better understanding of the detectors. The inconsistency between the recent muon ($g-2$) measurement [4] and its SM prediction is not so significant, particularly since the different SM computations [5] are not yet in complete agreement with one another. Therefore we must acknowledge that the SM reigns supreme up to the weak scale of order 100 GeV, successfully accounting for a huge set of experimental data spanning over a wide range of energy.

Then why do we at all bother about going beyond the SM? Actually a number of theoretical prejudices suggest that the SM is a very good effective description of Nature valid up to the weak scale. The SM gauge group is arbitrary. We do not understand the electroweak symmetry

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breaking mechanism, particularly, what makes the scalar mass-square negative. The SM cannot answer why there are only three chiral generations. The SM has no reply to the question as to why the weak scale is so light compared to the Planck scale. It also cannot turn on gravity within its framework. Besides, the SM has as many as 18 free parameters. All these indicate that the SM may not be the complete story.

As regards the experimental data, even though it seems that everything fits so well within the SM framework, there is some problem in the paradise! At least in one place the SM is in genuine trouble – this is to explain the ‘non-zero’ mass of a neutrino as suggested by the neutrino oscillation data. Since the SM does not contain a right-handed neutrino, it is not possible to account for the neutrino mass within the renormalizable part of the SM Lagrangian. Without changing the SM field content, one can indeed generate a non-zero neutrino mass through the following dimension-5 non-renormalizable operator

$$\frac{1}{\Lambda} \overline{L^C} L H H \rightsquigarrow m_\nu \sim \frac{\langle H \rangle^2}{\Lambda}, \quad (1)$$

giving a Majorana mass suppressed by a high scale Λ . Putting $m_\nu \sim 0.1$ eV (the choice is motivated by the Super-Kamiokande atmospheric neutrino data), we obtain $\Lambda \sim 10^{15}$ GeV, which is tantalizingly close to the Grand Unification scale! This can be interpreted [6] as a sort of indirect hint of a new physical scale between $M_Z \sim 92$ GeV and $M_{Pl} \sim 10^{19}$ GeV!

All these suggest that at higher energies (i.e., shorter distances) something beyond the SM becomes operative. But we cannot indulge ourselves in wild thinking in new physics model building, since lots of data are now there putting some kind of a discipline to our imagination. According to majority ‘supersymmetry’ [7, 8] is the most attractive option to describe physics beyond the SM.

1.1 What is supersymmetry?

Supersymmetry is a new space-time symmetry interchanging bosons and fermions, i.e., it is a symmetry between states of different spin. As an example, a spin-0 particle can be mapped to a spin- $\frac{1}{2}$ particle by a supersymmetry transformation. In supersymmetry, the Poincare group is extended by adding two additional generators Q and \bar{Q} , which are anticommuting, to the existing p (linear momentum), J (angular momentum) and K (boost), such that $\{Q, \bar{Q}\} \sim p$. Since the new symmetry generators are spinors, not scalars, supersymmetry is not an internal symmetry. Years ago, Dirac postulated a doubling of states by introducing antiparticle to every particle to reconcile Special Relativity with Quantum Mechanics. In Stern-Gerlach experiment, an atomic beam in an inhomogeneous magnetic field was shown to split due to doubling of the number of electron states into spin-up and -down modes. This indicated a doubling of states with respect to angular momentum. So it is no surprise [9] that Q would cause a further splitting into particle and superparticle ($f \xrightarrow{Q} f, \tilde{f}$). Since Q is spinorial, the superpartners differ from their SM partners in spin. The superpartners of fermions, called sfermions, are scalars, and those of gauge bosons, called gauginos, are fermions. They are clubbed together to form supermultiplets. The two irreducible supermultiplets which are used to construct the supersymmetric standard model are the ‘chiral’ and the ‘vector’ supermultiplets. The chiral supermultiplet contains a scalar ϕ and a 2-component Majorana fermion ψ . The vector supermultiplet contains a gauge field A_μ and a 2-component Majorana fermion λ (gaugino). The generic features of a supermultiplet are:

- There is an equal number of bosonic and fermionic degrees of freedom in a supermultiplet.

- Since p^2 commutes with Q , the bosons and fermions in a supermultiplet are mass degenerate.

The minimal supersymmetric standard model (MSSM) is the supersymmetric extension of the SM which has the minimal particle content: two complex Higgs doublets (the SM has only one) and their superpartners, the SM fermions and gauge bosons and their superpartners. The quartic scalar coupling is related to the gauge coupling; in that sense it has one less parameter than in the SM when supersymmetry is unbroken. There is an additional parameter μ which controls the mixing between the Higgs supermultiplets. It should be noted that supersymmetry has to be broken in order to explain the non-observation of any superparticle to date, and this introduces additional parameters. The scalar and gaugino masses, the trilinear scalar couplings (A parameters) and the bilinear Higgs mixing parameter (B_μ) are these additional parameters. In the absence of a precise knowledge about supersymmetry breaking, these parameters are in general free and unrelated to one another. The number of such parameters will be counted later. The MSSM field contents are summarised in Table 1.

Table 1: The particles in the minimal supersymmetric standard model.

Particles/superparticles	spin 0	spin 1/2	$SU(3) \otimes SU(2) \otimes U(1)$
leptons, sleptons (L) (in 3 families) (E^c)	$(\tilde{\nu}, \tilde{e}_L)$ \tilde{e}_R^*	(ν, e_L) e_L^c	$(1, 2, -1/2)$ $(1, 1, 1)$
quarks, squarks (Q) (in 3 families) (U^c) (D^c)	$(\tilde{u}_L, \tilde{d}_L)$ \tilde{u}_R^* \tilde{d}_R^*	(u_L, d_L) u_L^c d_L^c	$(3, 2, 1/6)$ $(\bar{3}, 1, -2/3)$ $(\bar{3}, 1, 1/3)$
Higgs, higgsinos (H_u) (H_d)	(H_u^+, H_u^0) (H_d^0, H_d^-)	$(\tilde{H}_u^+, \tilde{H}_u^0)$ $(\tilde{H}_d^0, \tilde{H}_d^-)$	$(1, 2, 1/2)$ $(1, 2, -1/2)$
Particles/superparticles	spin 1	spin 1/2	$SU(3) \otimes SU(2) \otimes U(1)$
gluon, gluino	g	\tilde{g}	$(8, 1, 0)$
W bosons, winos	W^\pm, W^0	$\tilde{W}^\pm, \tilde{W}^0$	$(1, 3, 0)$
B boson, bino	B^0	\tilde{B}^0	$(1, 1, 0)$

1.2 Why supersymmetry?

- Supersymmetry protects the electroweak hierarchy from destabilizing divergences.

The infamous ‘hierarchy problem’, i.e., why $M_{\text{Pl}} \gg M_W$, or equivalently, $G_N \ll G_F$, is the main motivation behind the introduction of supersymmetry [10, 11, 12]. It should be noted that the fermion masses are protected by chiral symmetry and the gauge boson masses by gauge symmetry. But there is no such protection mechanism for a scalar. In the SM, $m_H \sim M_W$, both being proportional to the Higgs vacuum expectation value (VEV). The

quantum correction to the Higgs mass is $\delta m_H^2 = \mathcal{O}(\alpha/\pi)\Lambda^2$, where Λ is the ultraviolet cut-off scale reflecting the appearance of new physics. It is nevertheless possible to bring down the Higgs mass to weak scale by adjusting the counter-term to cancel this large quantum correction. But this adjustment has to be done order by order and such fine-tuning of one part in 10^{17} to keep the Higgs mass at the weak scale makes the theory sick. The requirement of such an unnatural cancellation is at the root of the hierarchy problem. We note at this point that quantum corrections to the Higgs mass from a bosonic loop and a fermionic loop have *opposite* sign. So if the couplings are same and the boson is mass degenerate with the fermion, the correction would vanish! What can be a better candidate than supersymmetry to do this job? For every particle supersymmetry provides a mass degenerate partner differing by spin $\frac{1}{2}$. However, the cancellation is not exact because in real world supersymmetry is broken. But it has the virtue that it makes the Higgs mass quantum correction milder: $\delta m_H^2 = \mathcal{O}(\alpha/\pi)\delta m^2$, where δm^2 is the splitting between partners and spartners. Clearly, $\delta m_H^2 < m_H^2$, if $\delta m^2 < 1 \text{ TeV}^2$.

- Supersymmetry leads to unification of gauge couplings.

This is another motivation [13]. In the SM, when the gauge couplings are extrapolated to high scale, with their low energy measurements as input values for the calculation of their running, they do not meet at a single point. In supersymmetry, they do, at a scale $M_{\text{GUT}} \sim 2 \times 10^{16} \text{ GeV}$. The requirement is that the superparticles weigh around 1 TeV. In other words, supersymmetry has the right particle content to ensure that the gauge couplings can unify. This could be just an accident, but may be taken as a strong hint in favour of the Grand Unified theories (GUT). In the same spirit, we may expect that other supersymmetric couplings and soft masses also unify.

- Supersymmetry prefers a heavy top quark, and the top is indeed heavy.

Supersymmetry has two Higgs doublets. Due to heavy top quark induced radiative correction, the mass-square of one of the Higgs bosons, the one that couples to the up quark, starting from a positive value in the ultraviolet becomes negative in the infrared triggering electroweak symmetry breaking (EWSB). In the SM, the negative value of scalar mass-square is completely *ad hoc* and is put in by hand to ensure EWSB. In supersymmetry it is the heavy top quark that induces the flip of sign of one scalar mass-square. Also, it is quite amazing that it is the Higgs that becomes tachyonic during renormalization group running.

- Supersymmetry prefers a light Higgs, and the Higgs is expected to be light.

Supersymmetry predicts that the lightest neutral Higgs is lighter than M_Z at tree level. Due to the heavy top quark induced radiative correction it can at most go up to $\sim 150 \text{ GeV}$. Even though the Higgs has not yet been found, the precision electroweak data suggest that it should lie within 195 GeV at 95% CL, while the direct lower limit from LEP II is $m_H > 113.5 \text{ GeV}$ at 95% CL.

Also, if $m_H \sim 115 \text{ GeV}$ (the hinted value!), the SM effective potential becomes unstable above $\Lambda \sim 10^6 \text{ GeV}$. This can be rectified only by invoking a ‘supersymmetry-seeming’ set of new physics [14].

- Supersymmetry is a decoupling theory.

Supersymmetry decouples from precision measurements of the Z -pole observables. In other words, supersymmetry contributions vanish as superparticle masses are pushed to infinity.

On the contrary, simple technicolour models do not decouple and they are ruled out from precision electroweak measurements.

- Supersymmetry provides a cold dark matter candidate.

If the gluino, the superpartner of gluon, is around 1 TeV, then the GUT boundary conditions imply that the lightest supersymmetric particle (LSP) is around 100 GeV. Consistency with cosmology demands that the LSP is colour and electrically neutral [15]. The LSP interacts weakly with other particles and has properties which make it a natural candidate for cold dark matter of the universe. However, one necessary condition for this is that the LSP is stable. We will see later that in some supersymmetric models the LSP decays into the SM particles.

- Supersymmetry provides a framework to turn on gravity.

Using supersymmetry as a local symmetry leads to supergravity models. This is how gravity can be unified with all other interactions.

- Supersymmetry can explain the neutrino oscillation data.

Supersymmetric models with broken lepton numbers can reproduce the neutrino masses and mixing angles compatible with the recent neutrino oscillation data.

1.3 Where are the superparticles?

Not a single superparticle has been found to date! The lower limits from direct searches at colliders on the masses of generic sleptons (\tilde{l}) and squarks (\tilde{q}), gluino (\tilde{g}), lightest chargino ($\tilde{\chi}_1^\pm$) and the lightest neutralino ($\tilde{\chi}_1^0$) are

$$\begin{aligned} m_{\tilde{l}} &> \sim 100 \text{ GeV} \quad (\text{LEP II}), \\ m_{\tilde{q}} \sim m_{\tilde{g}} &> \sim 300 \text{ GeV} \quad (\text{Fermilab Tevatron}), \\ m_{\tilde{\chi}_1^\pm} &> \sim 100 \text{ GeV} \quad (\text{LEP II}), \\ m_{\tilde{\chi}_1^0} &> \sim 30 \text{ GeV} \quad (\text{using GUT relations}). \end{aligned} \tag{2}$$

Eq. (2) shows that supersymmetry is not only broken, it is very badly broken!

Since supersymmetry has lots of unknown parameters, translating experimental data into allowed/excluded multidimensional supersymmetry parameter space is a complicated job. First we have to decide what we are expecting to observe, and then we have to design our devices to detect them. Superparticles are expected to be produced in pairs, and if the LSP is stable, then the missing energy the latter carries constitutes the characteristic signature for supersymmetry search. For detailed and instructive discussions on the production and decay of superparticles in different colliders, see, for example, the reviews by Martin (hep-ph/9709356), Gunion (hep-ph/9704349), Tata (hep-ph/9706307) and Dawson (hep-ph/9612229). For a review on how to look for supersymmetry in the next linear collider (NLC), see the recent Snowmass report [16].

For indirect constraints on supersymmetry parameter space from electroweak precision data, $b \rightarrow s\gamma$, $(g-2)_\mu$, cosmology, etc., the readers are referred to, for example, [17], [18], [19]. One recent analysis [17] suggests that the quality of electroweak fit improves with light superpartners! Admitting sneutrinos in the range 55-80 GeV and charged sleptons marginally above their experimental lower limit fit the data better than just the SM alone!

2 Supersymmetry breaking

Let us first consider the spontaneous breaking of supersymmetry. There is a difference between an internal symmetry breaking and supersymmetry breaking. The latter requires $\langle 0|H|0\rangle > 0$, where $H = \frac{1}{4} \sum Q_\alpha^2$. Consider a situation in which $V(\phi) = 0$ for $\phi = v \neq 0$, and $V(0) > 0$, where V is the scalar potential, and ϕ is a scalar field which obtains a VEV v (e.g., consider the so called Mexican Hat potential of the SM). Here gauge symmetry is broken but supersymmetry is unbroken. Now consider a different situation in which V is symmetric about $\phi = 0$, with $V(0) = V_{\min} = E > 0$. Here gauge symmetry is unbroken, but supersymmetry is broken.

There are two important points [10]:

- When supersymmetry is spontaneously broken, a massless Goldstone fermion is generated. Remember, it is not simply a massless fermion (like neutrino), Goldstone fermion is a massless fermion that is created from vacuum by the supersymmetry current:

$$\langle 0|S_{\mu\alpha}|\psi_\beta\rangle = (\gamma_\mu)_{\alpha\beta}f; \quad Q_\alpha = \int d^3x S_{0\alpha}; \quad E = f^2, \quad (3)$$

where f is the coupling of the supercurrent to the Goldstone fermion and E , as stated previously, is the vacuum energy density.

- If $f = 0$ at tree level, it remains zero at all order.

But if supersymmetry is spontaneously broken at tree level in the observable world, it immediately leads to a disaster! The reason is the presence of a mass sum rule [20]

$$\text{STr}M^2 = \sum_{J=0}^1 (-)^{2J} (2J+1) \text{Tr}M_J^2 = X, \quad (4)$$

where J is the spin of the particle, and X corresponds to the trace of the group generators. $X = 0$ for any U(1) trace-anomaly free models, e.g., the supersymmetric standard model. This sum rule creates a major threat, since it predicts the existence of a charge 2/3 squark not heavier than the lightest charge 2/3 quark, and/or, a charge $-1/3$ squark not heavier than the lightest charge $-1/3$ quark [11]. In view of the non-observation of any superparticle to date, both results are experimentally ruled out. One way to tackle this problem is to admit explicit breaking of supersymmetry. At the same time we must ensure that the hierarchy between the Planck scale and the weak scale is not destabilized by such an action, because that was after all the motivation behind introducing supersymmetry in the first place. The terms which break supersymmetry explicitly but do not regenerate the quadratic divergences are called ‘soft terms’. In fact, supersymmetry breaking is implemented by admitting explicit mass terms for the scalars in the chiral multiplets and gauginos in the vector multiplets, and additionally by introducing the bilinear Higgs mixing (B_μ term) and trilinear scalar interaction (A terms) in the soft Lagrangian. The mass dimension of the soft terms in the Lagrangian must be ≤ 3 . We must however keep in mind that these soft terms are not quite arbitrary, as otherwise it would be difficult to satisfy many experimental constraints, e.g., the suppression of flavour-changing neutral currents.

But what is the origin of these soft terms? The usual prescription is the following: Supersymmetry is spontaneously broken in a ‘hidden sector’ which has no (or very small) interactions with the ‘visible sector’ supermultiplets. But the two sectors share some common interactions which mediate the information of supersymmetry breaking from the hidden sector to the observable world. The result is the appearance of calculable soft terms in the observable sector Lagrangian. This prescription leads to different mediation mechanisms of supersymmetry breaking. These mechanisms differ in the way the soft masses are generated and related to one another.

2.1 Supergravity

In supergravity (SUGRA) models [21], global supersymmetry is promoted to local supersymmetry. Supersymmetry is broken in the hidden sector and the message is transmitted to the observable sector by $(1/M_{\text{Pl}})$ -suppressed operators. Analogous to the Higgs mechanism in the SM, there is a super-Higgs mechanism operative here in which the gravitino ‘eats up’ the Goldstino and becomes massive. The gravitino mass ($m_{3/2}$) is therefore a ‘hard’ parameter which has its origin in the hidden sector. The essential points are:

- Denoting the supersymmetry breaking scale by \sqrt{F} , one can express $m_{3/2} \sim F/M_{\text{Pl}}$. For $m_{3/2} \sim 1$ TeV, we obtain $\sqrt{F} \sim 10^{11}$ GeV.
- The soft scalar masses $\tilde{m}^2 \propto G_N \propto 1/M_{\text{Pl}}^2$. Therefore, $\tilde{m}^2 \sim F^2/M_{\text{Pl}}^2$, i.e. $\tilde{m} \sim m_{3/2} \sim 1$ TeV.
- The μ problem is solved by the Giudice-Masiero mechanism [22], in which the μ -term is generated only at the time of supersymmetry breaking as a consequence of the observable sector’s interaction with the hidden sector. The Higgs mixing part is

$$\int d^2\bar{\theta} z^* \hat{H}_d \hat{H}_u / M_{\text{Pl}}, \quad (5)$$

where z is a hidden sector spurion field which obtains an F -term vev $F_z \bar{\theta}^2$ ($\bar{\theta}$ = Grassmann variable). F_z breaks supersymmetry, and at the same time generates $\mu \sim F_z/M_{\text{Pl}} \sim 1$ TeV.

- There are 4 free parameters and 1 sign: the common scalar and gaugino masses m_0 and $M_{1/2}$ respectively, the common trilinear A parameter, the bilinear B_μ parameter (all at the unification scale), and the sign of the μ parameter.
- The lightest supersymmetric particle (LSP) is the lightest neutralino. The supersymmetry search strategies are based on the characteristic missing energy signature.

A closer look to the soft-breaking terms reveals that the Kahler potential generates a mass term of the form $C_{ab} \phi_a^\dagger \phi_b$, where $C_{ab} = h_{ab} F^2 / M_{\text{Pl}}^2$, with a and b being the generation indices. There is no guarantee that the coupling h will be flavour diagonal. The real source of this Planck scale suppressed coupling lies in integrating out some of the Planck scale states which may couple to both hidden and observable sectors. Unless these couplings are flavour diagonal at high energy, we cannot control the magnitudes of the flavour off-diagonal couplings at low energy. On the other hand, experimental constraints (like Δm_K , $\mu \rightarrow e\gamma$, etc.) at low energy imply that flavour changing neutral currents are highly suppressed. The lack of explanation as to why these couplings would be flavour diagonal (i.e. $C_{ab} = C\delta_{ab}$) at high scale within the framework of supergravity gives rise to the ‘supersymmetric flavour problem’.

2.2 Gauge mediation

Gauge mediated supersymmetry breaking (GMSB) models [23] have been formulated primarily for the purpose of removing the supersymmetric flavour problem. Here gauge interactions rather than gravity are used to transmit the message of supersymmetry breaking. In this framework, there is a hidden sector where supersymmetry is broken, and in between the hidden and observable sectors there is a messenger sector. The messenger particles have couplings with standard gauge bosons and are aware of supersymmetry breaking since they have direct interactions with hidden

sector fields as well. Consider the superpotential: $W = \lambda X M \bar{M}$, where X is a hidden sector field and M and \bar{M} are messenger sector fields which could be a 5 and $\bar{5}$ or a 10 and $\bar{10}$ of $SU(5)$. $\langle X \rangle$ breaks $U(1)_R$ symmetry (discussed later) and $\langle F_X \rangle \equiv F$ breaks supersymmetry. The messenger scalars are then split as $m_{\pm}^2 = m^2 \pm F$. The main features of GMSB models are:

- Gaugino mass is generated at one-loop at the messenger scale M . One obtains

$$m_{\lambda}^i \sim \frac{\alpha_i}{4\pi} \frac{F \langle X \rangle}{M^2}, \quad (6)$$

i.e., non-zero gaugino mass requires the breaking of both R symmetry and supersymmetry.

- Scalar masses are generated at two-loop order at the scale M .

$$\tilde{m}^2 = 2n(F/M)^2 \sum_{i=1}^3 C_i \left(\frac{\alpha_i^2(M)}{4\pi} \right), \quad (7)$$

where n is the number of messenger multiplets, and C_i 's are the quadratic Casimir coefficients for the different representations to which the scalars belong. Clearly, squark masses being proportional to strong coupling constant are heavier than sleptons. Also note that even though squark masses are generated in two-loop, and gaugino masses in one-loop, the former appear as squared masses while the latter linearly, and hence both are of the same order.

- The μ term is generated at one-loop but B_{μ} in scalar potential is generated at two-loop. Still, this is very difficult to achieve. The ‘ μ problem’ is rather serious in GMSB models [24]. The trilinear A parameter is generated at two-loop, and at electroweak scale is not very large.
- The messenger scale M can be as low as 100 TeV. This means that a squark mass of ~ 100 GeV is consistent with a $\sqrt{F} \sim 100$ TeV. Recall that in SUGRA scenario \sqrt{F} is several orders of magnitude larger. For this reason the GMSB models are often cited as the ‘low scale supersymmetry breaking models’.
- The gravitino is superlight: $m_{3/2} \sim F/M_{\text{Pl}} \sim 0.1$ eV or so! Gravitino emission from hard photons or from selectrons constitutes the ‘smoking gun’ signals.

2.3 Anomaly mediation

The motivation is again to solve the flavour problem. In this scenario [25] the hidden sector is in one brane and the observable sector is in a different brane. Supersymmetry breaking takes place in the hidden sector and is transmitted to the observable sector via superconformal anomaly. Unlike in the SUGRA scenario, here there is no Kahler coupling between the hidden and the observable sectors, and this way the soft terms become ultraviolet insensitive. The ‘flavour problem’ is thus taken care of. Superconformal anomaly gives rise to a non-zero trace of energy-momentum tensor, and as a result soft masses are generated being proportional to the beta function of the corresponding interaction. The main features of this anomaly mediated supersymmetry breaking (AMSB) models are:

- Gaugino masses are proportional to the gauge beta functions: $\widetilde{M}_i \propto \beta_i m_{3/2}$. More precisely,

$$\widetilde{M}_3 = -\frac{3\alpha_s}{4\pi} m_{3/2}; \quad \widetilde{M}_2 = \frac{\alpha}{4\pi \sin^2 \theta_w} m_{3/2}; \quad \widetilde{M}_1 = \frac{11\alpha}{4\pi \cos^2 \theta_w} m_{3/2}. \quad (8)$$

This means $\widetilde{M}_3 : \widetilde{M}_2 : \widetilde{M}_1 = 1 : -0.1 : -0.3$, i.e., the Wino is the lightest neutralino. This should be compared with the SUGRA gaugino mass relation: $\widetilde{M}_3 : \widetilde{M}_2 : \widetilde{M}_1 = 1 : 0.3 : 0.17$.

- The soft scalar masses are given by

$$\widetilde{m}^2 = -0.25 \left(\frac{\partial \gamma}{\partial g} \beta_g + \frac{\partial \gamma}{\partial y} \beta_y \right) m_{3/2}^2, \quad (9)$$

where $\gamma = c_0 g^2 + d_0 y^2$, $\beta_g = -b_0 g^3$, $\beta_y = y(e_0 y^2 + f_0 g^2)$, with g and y being the gauge and Yukawa couplings. Since the SU(3) gauge beta function is negative while the SU(2) and U(1) gauge beta functions are positive, it immediately follows from the above mass relation that the sleptons are ‘tachyonic’. Phenomenologically, one tackles this problem by putting in an universal m_0^2 by hand to all scalar masses. A convincing theoretical reasoning regarding the origin of m_0^2 is still lacking.

- AMSB soft masses are renormalisation group invariant. Hence they are completely determined by their known low energy gauge and Yukawa couplings and hence make no reference to their high energy boundary conditions. However, the universal m_0 , which is thrown in to solve the tachyonic slepton problem, spoils this invariance.
- The spectrum is defined in terms of 3 parameters and 1 sign: $m_{3/2}$, m_0 , $\tan \beta$, and the sign of the μ .

The near degeneracy between the lighter chargino and the wino dominated neutralino LSP is the issue that one employs to constitute the clinching test of this scenario. The chargino will decay into LSP and a ‘very soft’ pion and this decay will give rise to a displaced vertex. Triggering such events though is not an experimentally easy task!

3 The parameters in a general supersymmetric model

In a general supersymmetric model, where we do not assume any particular mediation mechanism and do not impose any GUT conditions, the soft parameters are not related to one another. In this section, we will see how a general supersymmetric model can be parametrized [26]. We will also count the number of parameters required for this purpose.

First consider the superpotential, written in terms of the ‘chiral superfields’, as

$$W = \sum_{ij} \left(h_e^{ij} \hat{L}_i \hat{H}_d \hat{E}_j^c + h_d^{ij} \hat{Q}_i \hat{H}_d \hat{D}_j^c + h_u^{ij} \hat{Q}_i \hat{H}_u \hat{U}_j^c \right) + \mu \hat{H}_d \hat{H}_u. \quad (10)$$

Above, the sum is over the different generations. \hat{H}_d and \hat{H}_u are the two Higgs doublet superfields. The former gives masses to down-type quarks and charged leptons and the latter gives masses to up-type quarks. \hat{L} and \hat{Q} are lepton and quark doublet superfields; \hat{E}^c , \hat{D}^c and \hat{U}^c are the singlet charged lepton, down quark and up quark superfields respectively. h_e , h_d and h_u are the Yukawa couplings and μ is the Higgs mixing parameter. The usual convention is to put a ‘hat’ over a superfield, and without that ‘hat’ the symbol represents the scalar component within that superfield.

The Lagrangian is given by

$$-L = \sum_i \left| \frac{\partial W}{\partial \phi_i} \right|^2 + \sum_{ij} \frac{\partial^2 W}{\partial \phi_i \partial \phi_j} \psi_i \psi_j + \frac{1}{2} \sum_\alpha |D_\alpha|^2 + \sum_{ij\alpha} \sqrt{2} g_\alpha \psi_i (T^\alpha)_j^i \phi_j^* \lambda_\alpha, \quad (11)$$

where ϕ_i and ψ_i the generic scalar and fermion fields within the i th chiral multiplet, and λ_α represents the gaugino which is a Majorana fermion in the vector multiplet with α as the gauge group index. The D term is given by $D_\alpha = -g_\alpha \phi_i (T^\alpha)_j^i \phi_j^*$.

The soft breaking terms are given by

$$\begin{aligned} -L_{\text{soft}} = & \sum_{ij} \tilde{m}_{ij}^2 \phi_i^* \phi_j + \sum_{ij} \left(A_e^{ij} L_i H_d E_j^* + A_d^{ij} Q_i H_d D_j^* + A_u^{ij} Q_i H_u U_j^* \right) \\ & + (B_\mu H_d H_u + h.c.) + \frac{1}{2} \sum_\alpha \tilde{M}_\alpha \lambda_\alpha \lambda_\alpha. \end{aligned} \quad (12)$$

3.1 Counting parameters

Let us now count the total number of real and imaginary parameters in a general supersymmetric model with 2 Higgs doublets. This will also become relevant when we will discuss CP violation [27]. Each Yukawa matrix h_f in Eq. (10) has 9 real and 9 imaginary parameters, and there are 3 such matrices. Similarly, each A_f matrix in Eq. (12) has 9 real and 9 imaginary parameters, and again there are 3 such matrices. The scalar mass square \tilde{m}_{ij}^2 can be written for 5 representations: Q, L, U^c, D^c, E^c . For each representation, the (3×3) hermitian mass square matrix has 6 real and 3 imaginary parameters. Finally, we have 3 gauge couplings (3 real), 3 gaugino masses (3 real and 3 imaginary), μ and B_μ parameters (2 real and 2 imaginary), $(m_{H_u}^2, m_{H_d}^2)$ (2 real), and θ_{QCD} (1 real). Summing up, there are 95 real and 74 imaginary parameters. Are all of them physical? The answer is: No! If we switch off the Yukawa couplings and the soft parameters, i.e., turn on *only* gauge interactions, there is a global symmetry, given by

$$G_{\text{global}} = U(3)^5 \otimes U(1)_{\text{PQ}} \otimes U(1)_R. \quad (13)$$

The Peccei-Quinn (PQ) and R symmetries will be discussed in the next two subsections. $U(3)^5$ symmetry means that a unitary rotation to the 3 generations for each of the 5 representations leaves the physics invariant. However, this unitary symmetry is broken. Once a symmetry is broken, the number of parameters required to describe the symmetry transformation can be removed. For example, when a $U(1)$ symmetry is broken, we can remove one phase. Since a $U(3)$ matrix has 3 real and 6 imaginary parameters, we can remove 15 real and 30 imaginary parameters from the Yukawa matrices once $U(3)^5$ is broken. As we will see, the PQ and R symmetries are also broken. So we can remove 2 more imaginary parameters. But even when all the Yukawa couplings and soft parameters are turned on, there is a still a global symmetry

$$G'_{\text{global}} = U(1)_B \otimes U(1)_L, \quad (14)$$

where B and L are baryon and lepton numbers. Hence we can remove not 32 but only 30 imaginary parameters. Thus we are left with $95 - 15 = 80$ real and $74 - 30 = 44$ imaginary, i.e., a total of 124 independent parameters. The SM had only 18. So supersymmetry gifts us 106 more! In the SM we had only one CP violating phase. Now we have 43 new phases which are CP violating!

3.2 Peccei-Quinn (PQ) symmetry

If we put $\mu = 0$ in Eq. (10), W is invariant under the following global $U(1)$ transformation:

$$\hat{H}_{d(u)} \rightarrow e^{i\alpha} \hat{H}_{d(u)}, \hat{Q}(\hat{L}) \rightarrow e^{-i\alpha} \hat{Q}(\hat{L}), \hat{E}^c \rightarrow \hat{E}^c, \hat{D}^c \rightarrow \hat{D}^c, \hat{U}^c \rightarrow \hat{U}^c. \quad (15)$$

This is a PQ symmetry, and it is preserved as long as $\mu = 0$. Note that if $\mu = 0$, the B_μ parameter in Eq. (12) is also zero. Now consider the scalar minimization condition: $B_\mu = m_A^2 \sin 2\beta$, where $\tan \beta = v_u/v_d = \langle H_u \rangle / \langle H_d \rangle$. If $B_\mu = 0$, two cases may arise: (1) either $v_d = 0$ or $v_u = 0$, i.e., some quarks/charged leptons are massless, (2) $m_A = 0$. Both cases are experimentally ruled out. Hence $\mu \neq 0$, and the PQ symmetry is broken. Consistency with phenomenology requires μ to be within 1 TeV.

But μ is a superpotential parameter and hence there is no reason for it to be zero in the limit of exact supersymmetry. In fact it could in principle be as high as the GUT or Planck scale. Then the question is what makes it to weigh in the ball-park of other supersymmetry breaking masses? This is the origin of the so called ‘ μ problem’.

3.3 R symmetry

Under this global U(1) symmetry, the superpotential $W \rightarrow W' = e^{2i\alpha}W$. This can be arranged by, for example, by the following choice:

$$\hat{H}_{d(u)} \rightarrow e^{i\alpha} \hat{H}_{d(u)}, \hat{Q}(\hat{L}) \rightarrow e^{i\alpha} \hat{Q}(\hat{L}), \hat{E}^c \rightarrow \hat{E}^c, \hat{D}^c \rightarrow \hat{D}^c, \hat{U}^c \rightarrow \hat{U}^c. \quad (16)$$

Note, $L = \int d^2\theta W$ is invariant under this rotation, where θ is the Grassmann variable. Therefore, $d\theta \rightarrow e^{-i\alpha}d\theta$ and $\theta \rightarrow e^{i\alpha}\theta$ (to ensure $\int d\theta\theta = 1$). Since a chiral superfield ($\hat{\phi}$) can be written in terms of its scalar (ϕ) and fermion (ψ) components as $\hat{\phi} = \phi + \psi\theta + F\theta^2$ (where F is the auxiliary parameter), it is clear that ϕ carries the same R charge as $\hat{\phi}$ and ψ carries one unit less. It immediately follows that for the Lagrangian in Eq. (11) to remain invariant, the gaugino picks up a non-zero R charge: $\lambda_\alpha \rightarrow e^{i\alpha}\lambda_\alpha$. It then follows from Eq. (12) that the gauginos are massless when R symmetry is exact. Also, the trilinear A terms are vanishing in the same limit. So R symmetry has to be broken for the construction of a realistic supersymmetric model.

3.4 CP violation in supersymmetry

For simplicity, let us consider the MSSM with common scalar and gaugino masses (\tilde{m} and \widetilde{M} respectively). We also assume $A_f = AY_f$. In this framework, there are 4 additional (compared to the SM) CP violating phases [28, 29, 27]. These are contained in the 4 parameters \widetilde{M} , A , B_μ and μ . But we will see that only 2 of the 4 phases are physical. To realise this, let us treat the above 4 parameters (appearing in Eqs. (10) and (11)) as spurions whose VEVs break the PQ and R symmetries. They are thus assigned the following PQ and R charges to compensate those of the fields described in Eqs. (15) and (16):

$$\mu : (-2, 0) \quad B_\mu : (-2, -2) \quad A : (0, -2) \quad \widetilde{M} : (0, -2), \quad (17)$$

where, for each parameter, the first number denotes the PQ charge and the second number the R charge. The arguments of only those combinations will give independent phases which have no net PQ and R charges. There are 2 such independent phases:

$$\phi_A = \text{Arg} (A^* \widetilde{M}), \quad \phi_B = \text{Arg} (\widetilde{M} \mu B_\mu^*). \quad (18)$$

These phases contribute to the electric dipole moment of the neutron as

$$d_N \sim 2 \left(\frac{100 \text{ GeV}}{\tilde{m}} \right)^2 \sin \phi_{A,B} \times 10^{-23} e \text{ cm} [30], \quad (19)$$

which should be compared with $d_N^{\text{exp}} < 6.3 \times 10^{-26} e \text{ cm}$ [31]. Generically we may expect $\tilde{m} \sim 100 \text{ GeV}$ and $\sin \phi_{A,B} \sim 1$, which violate the experimental bound by 2 orders of magnitude. This gives rise to the ‘supersymmetric CP problem’ [32]. The contribution to the ϵ_K parameter in the neutral K system [33] overshoots the experimental constraint by several orders of magnitude, unless one assumes (i) heavy and nearly degenerate (first two family) squarks, (ii) near alignment between quark and squark bases, and (iii) $\sin \phi_{A,B} \ll 1$.

In fact there is an intricate relationship between flavour violation and CP violation. Several flavour models, i.e., models with global horizontal symmetries (abelian [34], non-abelian with R -parity conservation [35], non-abelian with R -parity violation [36]), have been constructed, but there is no ‘the’ flavour model yet!

4 The Higgs bosons in supersymmetry

Supersymmetry requires two complex Higgs doublets [37]. Out of the 8 degrees of freedom they contain, 3 are ‘eaten up’ by W^\pm and Z , and the remaining 5 correspond to 5 physical Higgs bosons – two charged (H^\pm) and three neutral. Of the three neutral ones, one is CP odd (A) and two are CP even (H^0 and h^0). Their tree level masses are given by

$$\begin{aligned} m_A^2 &= m_{H_u}^2 + m_{H_d}^2 + 2|\mu|^2, \\ m_{H^\pm}^2 &= m_A^2 + M_W^2, \\ m_{h^0}^2 &= \frac{1}{2} \left[m_A^2 + M_Z^2 - \sqrt{(m_A^2 + M_Z^2)^2 - 4m_A^2 M_Z^2 \cos^2 2\beta} \right], \\ m_{H^0}^2 &= \frac{1}{2} \left[m_A^2 + M_Z^2 + \sqrt{(m_A^2 + M_Z^2)^2 - 4m_A^2 M_Z^2 \cos^2 2\beta} \right]. \end{aligned} \quad (20)$$

It immediately follows that $m_{H^\pm} \geq M_W$, $m_{H^0} \geq M_Z$ and $m_{h^0} \leq M_Z$ at tree level. The interesting thing to observe is the last inequality showing the existence of a light neutral Higgs boson. This is not really unexpected as the scalar quartic coupling in supersymmetry is related to the gauge coupling, unlike in the SM where it is a free parameter. But the radiative correction to $m_{h^0}^2$ grows as the fourth power of the top mass and hence is quite large [38]:

$$\delta m_h^2 = \mathcal{O}(\alpha) \frac{m_t^4}{M_W^2} \ln \left(\frac{m_t^2}{m_t^2} \right). \quad (21)$$

The radiative correction pushes the upper limit on m_{h^0} to about 150 GeV. This constitutes a clinching test of supersymmetry. If Higgs is not found within this limit, supersymmetry in its present form is ruled out, no matter how heavy one would like the superparticles to be.

5 Naturalness criterion

This is more an aesthetic point of view! When we do not understand the deeper structure of a theory responsible for the origin of some parameters used for an effective description of the theory, we do not generally expect that those parameters can be arbitrarily large such that a delicate cancellation among them may reproduce a small physical observable. In other words, a model is less ‘natural’ if it is more ‘fine-tuned’. Let us try to understand the situation in the context of supersymmetric theories. From the scalar potential minimization, we obtain

$$\frac{1}{2} M_Z^2 = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2 \beta}{\tan^2 \beta - 1} - \mu^2, \quad (22)$$

where $m_{H_u}^2 = m_{H_d}^2 - \Delta m^2$, where Δm^2 is the correction due to renormalization group running from the high scale to the electroweak scale. This correction crucially depends on the top quark Yukawa coupling. EWSB occurs when $m_{H_u}^2$ turns negative by way of Δm^2 overtaking $m_{H_d}^2$ such that a cancellation between the two terms on the RHS of Eq. (22) exactly reproduces the experimental Z -mass on the LHS of the same equation. Now notice that this is a cancellation between terms of completely different origin: the first term on the RHS of Eq. (22) involves soft scalar masses which appear in the scalar potential after supersymmetry breaking, while the second term, i.e. the μ term, arises as a result of hidden sector interaction and appears in the superpotential. How much cancellation between these completely uncorrelated quantities are we going to tolerate? Barbieri and Giudice (BG) [39] offered a criterion by introducing a quantity

$$\Delta_i \equiv \left| \frac{\partial M_Z^2 / M_Z^2}{\partial a_i / a_i} \right|, \quad (23)$$

where a_i are input parameters at high scale. Δ is a measure of fine-tuning. An upper limit on Δ can be translated into an *upper* limit on superparticle masses. BG had shown that with $\Delta = 10$, i.e., with $1/\Delta = 10\%$ fine-tuning, the upper limits on superparticle masses turn out to be around 1 TeV in the MSSM with universal boundary conditions. In GMSB models the naturalness problem is more serious since the right-handed selectron is significantly lighter than the Higgs (see, for example, Bhattacharyya and Romanino in [39]). A detailed analysis by Giusti, Romanino and Strumia [39] has claimed that only 5% of the MSSM parameter space is now experimentally allowed with a modest naturalness requirement. It should be admitted though that naturalness upper limits are rather subjective and should not taken as very strict or rigid limits.

6 R -parity violation in supersymmetry

Even if $U(1)_R$ symmetry is broken to ensure gaugino mass generation, a discrete symmetry, called R -parity, may survive. R -parity is defined as $R_p = (-1)^{3B+L+2S}$, where B and L are the baryon and lepton numbers respectively, and S is the spin of the particle. All SM particles have $R_p = 1$ and their superpartners have $R_p = -1$. However, it should be noted that R_p conservation is not ensured by gauge invariance or any other deep underlying principle. Hence in a general supersymmetric model R_p -violating interactions [40] should be included. Stringent constraints on the strength of R -parity violating interactions arise from the considerations of proton stability, $n-\bar{n}$ oscillation, neutrino-less double beta decay, charged-current universality, Δm_K and Δm_B , electroweak precision data from LEP, etc. For a collection of these limits, see [41] (and also the references within [41]).

The explicit R -parity violating superpotential is given by

$$W_{R_p} = \frac{1}{2} \lambda_{ijk} \hat{L}_i \hat{L}_j \hat{E}_k^c + \lambda'_{ijk} \hat{L}_i \hat{Q}_j \hat{D}_k^c + \frac{1}{2} \lambda''_{ijk} \hat{U}_i^c \hat{D}_j^c \hat{D}_k^c + \mu_i \hat{L}_i \hat{H}_u. \quad (24)$$

The first, second and the fourth terms are L -violating and the third is B -violating. There are 9 λ -type, 27 λ' type, 9 λ'' type and 3 μ_i couplings. Thus the above superpotential (24) introduces 48 new parameters to the already existing 106 in a general supersymmetric framework with R_p conservation. We briefly mention some important consequences of R_p violation:

- The LSP is no longer stable. So supersymmetry search strategies have to be redesigned, since the characteristic missing energy signature is now gone! One has to look for multilepton or multijet final states. For the impact of R_p -violating couplings at various colliders, see [42].

- Since the LSP is not stable, supersymmetry can no longer provide a cold dark matter candidate. One must look for an alternative.
- It is possible to generate Majorana neutrino masses with the L -violating couplings both at tree and at one loop level. The trilinear L -violating couplings induce one loop neutrino masses via fermion-sfermion loops, and the bilinear L -violating couplings contribute to the tree level mass via neutrino-neutralino mixing. The couplings within their experimental limits can explain the observed neutrino oscillation data [43].
- Complex R_p violating couplings can induce large CP violation in some B decay processes in which the SM predicts very small CP violation [44]. These effects can be tested in the ongoing and upcoming B factories.

7 Conclusion and Outlook

Some of the questions that guide our hunt for supersymmetry are:

- What we expect to be the first signal of supersymmetry? In which machine? And when?
- What is the scale of supersymmetry breaking? Is it high or low?
- Is there any hidden sector? How the information of supersymmetry breaking is transmitted from there to the observable world?
- What is the LSP? Can it account for the cold dark matter?
- Is R -parity violated?
- Is there a Grand Unification? When will the proton decay?
- What will be the most convincing solution to the supersymmetric flavour and CP problems?
- Why is μ at the weak scale?
- Are there extra dimensions? Do they help supersymmetric model building?

Only experimental data can uncover the truth. Supersymmetry has not been discovered at LEP. But Tevatron is running, LHC is due in 2006, NLC would hopefully be approved!

We have many models of supersymmetry breaking: SUGRA, GMSB, AMSB, Gaugino mediation, etc. These models are very predictive and address the flavour problems differently. They have only a few independent parameters. But Nature might not have chosen any one of those models to break supersymmetry!

Even though we are not quite sure how supersymmetry is broken, we know how to parametrize a general supersymmetric theory. The parameters are then independent. The final answer will come only after we measure all the 106 supersymmetry parameters (26 masses, 37 angles, 43 phases) in R -parity conserving case and 48 more if R -parity is violated. In fact, assuming charginos and neutralinos will be copiously produced in the NLC, analyses of how to disentangle the CP violating phases have already started [45].

We make a remark that the large number of parameters in a general supersymmetric model only reflects our lack of knowledge of the exact supersymmetry breaking mechanism. As a result, the predictions vary in a wide range in many cases depending on the choice of parameters. In this sense, supersymmetry is not simply just one model, it is rather a class of models.

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